Challenges in the Auto Industry Paradigm Shift from ICE to Electric

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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STS Research Paper

The Electric Vehicle Transition

In 2020 alone, the sales of electric cars worldwide rose by 43%, despite the overall automotive industry-wide decline in sales due to the COVID-19 pandemic (Carrington, 2021). The accelerating adoption of electric vehicle technology is arguably the largest paradigm shift in the history of the automotive industry. With the advancing threat of anthropogenic climate change, governmental policies, such as phase-out dates for the sale of new fossil fuel-powered vehicles, have spurred the automotive industry into action to develop new electric vehicle models and platforms to eventually supplant fossil fuel-powered counterparts (Wappelhorst, 2021). However, the process of the entire industry making such a large transition has come with associated challenges that many manufacturers need to face.

At the heart of every battery-electric vehicle (BEV), the currently dominant fully-electric vehicle technology, is a large lithium-ion battery pack. At the scale of the industry transition to electric vehicles, any challenges in the manufacturing of these battery packs can become a significant obstacle. The case of General Motors' (GM) Chevrolet Bolt EV catching on fire due to battery manufacturing defects is a major example of a disruption in an automaker's electric vehicle transition. With GM recalling all Bolts ever produced, numbering over 140,000 units (Eisenstein, 2021), the magnitude of this recall highlights the importance of examining this specific case, as well as more generally, the challenges in battery manufacturing and their wider impacts. Reviewing the wider context of these battery fires can also help gain a better understanding of how the adoption of electric vehicle technology is influenced, as well as lessons to be learned on how to better facilitate this critical paradigm shift to electric vehicles.

History of the Electric Car

While the fundamental technology behind electric vehicles has existed since the 19th century, it was never able to maintain widespread adoption. In its stead, the internal combustion engine (ICE), through its application in the automobile, transformed American life in the 20th century. The automobile made traveling long distances accessible, and when combined with the vastness of the United States, led to the automobile's position as the solution to personal mobility for much of American society. Thus, the history of the automobile and the technological changes currently happening within the automobile industry have an outsized impact and are important to examine.

In the nascent years of the automobile during the 19th century, there were three main power sources for automobiles: steam, gasoline, and batteries. The earliest forms of automobiles used steam power, which had the primary disadvantages of long startup times and constant water refills, making steam power fairly impractical (United States Department of Energy, 2014). When electric vehicles were first demonstrated in the 1830s by Scottish inventor Robert Anderson, they were only a novelty due to the energy storage technology (galvanic cells) being non-rechargeable. It took until the latter half of the 19th century, with the invention of the rechargeable lead-acid battery by French inventor Gaston Planté in 1859, and subsequent improvements by Camille Faure in 1881, that electric vehicles became reasonably usable (*Automobile - Early Electric Automobiles*, 2022). Gasoline-powered cars, by comparison, were noisy, polluting, required laborious hand-crank starts, and demanded significantly more maintenance. These distinct disadvantages of gasoline and steam led to the electric car attaining some early success; electric cars made up an estimated third of vehicles on American roads by 1900 (Auto Express, 2020). However, this success was relatively short-lived, largely due to a lack of electrical infrastructure and technological improvements with the internal combustion engine.

At the turn of the 20th century, Americans that lived outside of urban areas rarely had access to electricity, completely precluding their use of electric vehicles (United States Department of Energy, 2014). Early electric vehicles also had limited range, low speeds, and took extremely long to recharge (*Automobile - Early Electric Automobiles*, 2022). Then, with the advent of cheap and easily accessible gasoline as a result of the Texas oil boom, affordable gasoline cars such as the Model T, and the invention of the electric starter motor (eliminating the tedious hand-crank start procedure), the electric car soon fell out of favor (United States Department of Energy, 2014).

For most of the next century, the internal combustion engine was dominant. It was only until the latter half of the 20th century that the electric car made brief resurgences. In the 1960s and 1970s, interest in electric cars was briefly renewed due to the oil crises that led to major gasoline shortages and soaring gas prices, notably the 1973 Arab Oil Embargo. In the US, these oil crises drove the government to reduce dependence on foreign oil by funding development of alternative technologies with the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (United States Department of Energy, 2014). However, electric vehicle technology had not yet reached a point where it could feasibly supplant the now dominant ICE technology, as many of the same drawbacks from early electric vehicles still existed, including limited range due to the battery technology of the time.

By 1989, the issue of climate change was viewed as the major global issue of the next decade (Landsberg, 1989). Growing concern about climate change and global warming throughout the 1980s and 1990s had brought about another resurgence in interest for cleaner alternatives to the internal combustion engine. The 1990s saw landmark new environmentally-focused government actions and regulations at both the state and local levels, including the 1990 amendments to the Clean Air Act that established tighter restrictions on emissions from cars and trucks and most notably, a clean fuel car pilot program in California (*1990 Clean Air Act Amendment Summary: Title II*, 2021). The California Zero-Emission Vehicle (ZEV) mandate of 1990 required the seven top-selling automakers to have 2% of their auto sales in California be zero-emissions vehicles by 1998, with the percentage requirement increasing over time (Witzenburg, 2021). This spurred major automakers to begin building electric versions of existing ICE vehicles to save on development costs, compared to engineering an entirely new platform specifically for electric vehicles (United States Department of Energy, 2014).

Meanwhile, GM had already been taking the ambitious approach of engineering a new electric concept car from the ground up, called the Impact. This evolved into the EV-1, which served as a milestone in the history of the electric vehicle; it was the first mass-produced and purpose-built electric car from a major manufacturer in recent history (Witzenburg, 2021). However, the EV-1 program was ultimately ended in 2003 due to low consumer demand and high production costs, making it difficult for GM to justify continuing the program from a financial standpoint (*EV1 Electric Car*, 2017).

It was only until 2016 that GM began producing electric vehicles again. The new car, the Chevrolet Bolt, was its first major mass-produced electric car since the EV-1 program ended. However, the Bolt has faced major setbacks. In a debacle expected to cost GM over $2 billion dollars, the Chevrolet Bolt battery-electric vehicle made news headlines beginning in 2019 for multiple vehicles spontaneously catching fire. GM has had to issue three recalls, expanding the scope of the vehicles affected each time. As of late 2021, the issue is serious enough that the scale of the recall affects all Bolts ever produced, numbering approximately 141,000 units from model years 2016 to 2022 (Voelcker, 2021). GM attributes the root cause of the battery fires to manufacturing defects in the battery pack by its supplier, LG Chem, which result in a higher risk of fire occurring when the batteries are nearly fully charged or discharged too low.

The spate of Bolt battery fires, while catastrophically bad for GM's image, is not the only recent instance of battery-electric vehicle-related problems. Hyundai also needed to recall about 90,000 of its Kona EV models for the same issue after 15 fires. In Europe, Ford recalled 20,500 of its Kuga plug-in hybrid vehicles for battery overheating issues that had caused a handful of fires (Wayland & Kolodny, 2021). These examples show that the industry as a whole is facing many of the same common challenges. However, GM faces these common challenges, but also possesses challenges unique to "legacy" automakers like itself.

The Paradigm Shift from ICE to Electric

In the context of the field of Science, Technology and Society (STS), the concept of a paradigm shift is relevant to the discussion of the automotive industry's technological change from ICE technology to battery electric technology. The concepts of paradigms and paradigm shifts were first introduced by the American physicist and philosopher Thomas Kuhn in his influential 1962 book, *The Structure of Scientific Revolutions*. According to Kuhn (2012), paradigms are, "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners." This definition allows the idea of a paradigm to fit a large range of situations and characterize the state of scientific or technological progress.

An important point that Kuhn makes is that these paradigms don't stay fixed but evolve over time. Kuhn provides a description of the typical process through which this change happens.

One of the primary ideas about this process he put forward was that scientific progress does not generally happen in a continual linear trajectory. Instead it undergoes periodic revolutions in which beliefs or practices are revised, where these beliefs or practices refer to the current paradigm in a given area (Bird, 2018). Following from this, Kuhn (2012) defines the paradigm shift as a situation "in which an older paradigm is replaced in whole or in part by an incompatible new one," referring to those revolutionary phases. Importantly, Kuhn points out that these revolutionary phases are motivated by shortcomings or failings of the paradigms that are already in place in resolving "important anomalies," and don't necessarily happen out of chance or randomness (Bird, 2018).

The concept of a paradigm shift is not without its criticisms, as some believe it is too generalized, can be applied across too many disciplines, and is not conclusive. However, in context with the electrification of the automotive industry, the concept of a paradigm shift fits well and provides an opportunity to perform deeper and more structured analysis.

Methods

How have the challenges associated with the development and manufacturing of battery technologies for battery electric vehicles, such as GM's recent mass recall of the Chevy Bolt EV for the risk of battery fires, shaped the paradigm shift from internal combustion engine (ICE) vehicles to electric vehicles?

To help contextualize the current ICE-to-electric paradigm shift in the automotive industry, the intertwined history of battery and electric vehicle technology is examined to gain a better understanding of the long-standing obstacles to their widespread adoption. Additionally, looking at sources discussing recent issues related to battery-electric vehicles helps to characterize more recent challenges. In particular, the Bolt EV fires and ensuing recalls serve as a case study in the context of common issues that automakers have been facing, as well as the overall industry-wide shift to battery-electric vehicles. The sources are news articles and academic studies that fall into the two main categories of being specifically about a certain event, such as the Chevy Bolt fires, or more generally discussing a collection or group of incidents relating to battery-electric vehicles in general.

Results and Discussion

The paradigm shift from the technology of the internal combustion engine-powered automobile to the battery-electric automobile has not been a linear and straightforward path. The challenges faced by automakers during this paradigm shift show the complexities and difficulties in supplanting a well-established and refined technology with a new technology at scale. In particular, a fundamental paradigm shift in battery technology had to occur. Battery technology has historically served as a major obstacle to the adoption of the electric vehicle, primarily due to insufficient energy density. The development of relatively energy-dense lithium-ion batteries has allowed for the automobile industry to make a major paradigm shift away from bulky lead-acid batteries and develop vehicles with much longer, practical, driving ranges. However, lithium-ion batteries themselves continue to have significant drawbacks; further improvements to battery technology are arguably still needed. In addition to this necessary paradigm shift in battery technology, there are a wide range of necessary smaller paradigm shifts that are happening or still need to happen in both infrastructure and the way in which automakers operate, from the approach to engineering and designing vehicles to manufacturing and supply chains. Only when the new paradigms in these areas are established, can the electric vehicle find widespread adoption and feasibly supplant the internal combustion engine vehicle as the dominant paradigm.

Throughout the history of the automobile and the automotive industry, the dominant paradigm has primarily been the internal combustion engine, which has allowed the technology to be continually refined, while becoming embedded into many aspects of both the way automakers manufacture and the way entire industries operate. However, through the growing concern about greenhouse gas emissions and the associated issue of climate change starting in the 1980s and 1990s, focus became increasingly placed on challenging the ICE paradigm, which corresponds to the stage of a paradigm shift that Kuhn (2012) describes as “a state of crisis” in which the boundaries of the existing paradigm are pushed in an “exploratory” nature. As of the current day, the paradigm of the electric vehicle has only started to reach the “adoption” stage of a paradigm shift that Kuhn (2012) describes. General Motors’ EV-1 program in the late 1990s exemplifies an experimental challenge to the ICE paradigm.

In developing the EV-1, GM took an ambitious approach to electrification by developing an electric car from the ground up, even before the California ZEV mandate of 1990 (Witzenburg, 2021). This contrasted with the approach that other automakers took in order to comply with the California ZEV mandate of 1990, by redeveloping existing ICE vehicles into electric vehicles, which saved on development costs. However, the battery technology of the time was not ready and hampered the success of those 90s electric cars. In the case of the EV-1, to match the energy density of just a half-gallon of gasoline, a 1,175 lb lead acid battery pack was needed–but the car still only had a range of about 50-70 miles on a charge. As cold temperatures shortened the EV-1’s already limited range to be unacceptably low, GM limited the EV-1 to be only available through leases in a handful of warm-weather cities, such as Los Angeles (Witzenburg, 2021). The EV-1 enjoyed a second generation, in which the battery pack was upgraded to improve the rated range from 60 miles to 100 miles (Mendoza & Argueta, 2000). Despite this improvement, it wasn't enough to keep the EV-1 viable, as consumer demand was still low and the car was expensive for GM to produce (*EV1 Electric Car*, 2017).

Ultimately, the California Air Resource Board (CARB) relented on its original ZEV mandate; it was unrealistic to achieve due to the technology not yet being sufficiently ready. Following this, at the end of the three-year leases of the EV-1, GM ended the program and destroyed all but 40 examples of the car, which were stripped of their powertrains and donated to museums and universities (Witzenburg, 2021). The failure of the EV-1 can be partly traced back to the EV-1's impracticality; it was a two-seat car that had poor driving range and was only available in very specific markets, limiting its mass market appeal. More fundamentally, however, both the limited range and high production costs can be traced back to the battery technology of the time still not being ready to feasibly match the range and convenience of internal combustion engine cars. Many of these disadvantages, while significantly mitigated in some ways, are to some extent still present today and play a major role in the current industry shift to EVs.

Spurred on by both governmental pressure and consumer demand, the automobile industry's change-over in focus from producing fossil fuel-powered internal combustion engine vehicles to battery-electric vehicles can be considered individually as a major paradigm shift, but can also be looked at as a set of multiple smaller paradigm shifts that have occurred or are currently in progress. Of note are the paradigm shifts in the underlying battery technology, the necessary energy infrastructure that is critical to making electric vehicles viable, and even the way that automobile manufacturers themselves function and do business. In each case, they each fit the idea of a paradigm shift in that one paradigm is partly or fully replacing the old paradigm;

the way that something had previously been thought about or done is being changed in a significant way to address shortcomings or issues that plague existing solutions.

In the original paradigm of electric vehicle battery technology, lead-acid batteries were typically used to power electric vehicles. Having been originally invented in 1859, lead-acid batteries were a fairly refined technology by the end of the 20th century. However, with the advent of lithium-ion battery technology and the subsequent first commercially-produced lithium ion batteries in 1991 (Qiao & Wei, 2012), lead-acid batteries had significant comparative disadvantages–primarily in energy density. In applications such as the first generation EV-1, a large array of lead-acid batteries provided a rated 16.5 kWh of capacity while weighing 1,175 lb (Mendoza & Argueta, 2000). In comparison, the first generation Chevy Bolt EV utilized a lithium-ion battery pack that provided a comparatively massive 60 kWh of capacity while at the same time weighing far less, at only 960 lb (Sherman, 2016). This advantage in energy density has resulted in a near-complete paradigm shift in terms of battery pack technology used by modern electric vehicles from lead-acid to lithium-ion.

A major factor in the internal combustion engine's continued dominance can be partly attributed to the well-established nature of the necessary supporting infrastructure and the ability to refuel quickly. In the US, a driver can reliably depend on the availability and proximity to gas or diesel at gas stations lining nearly every major interstate highway exit. While gas stations in the US have steadily declined in number for the past two decades (Nedelea, 2022), they still number approximately 136,400 across the country. By contrast, there are only 43,800 electric vehicle charging stations (Sullivan & Taylor, 2021).

The paradigm of the filling station has the distinct advantage of ubiquity and convenience, in addition to the relatively short time required to refill a tank of gas or diesel.

Outside of Tesla, which operates its own Supercharger charging network of more than 25,000 stations (Sullivan & Taylor, 2021), EV charging stations can vastly vary in quality and charging speeds, serving as a significant obstacle to more widespread EV adoption. Even with properly working and the fastest charging speeds, charging an EV on long road trips can add significant amounts of time. After making an 8 hour road trip in a Polestar 2 EV from San Francisco to Southern California, Sullivan and Taylor (2021) found that, with the Polestar 2's fairly standard rated range of 265 miles, it became troublesome to stop for about 45 minutes every 200 miles. There was no shortage of charging stations along their route, but the amount of time required to recharge meant that, without any significant advances in charging speed, as the number of EVs on the road increases, long charge times could create bottlenecks at charging stations.

These disadvantages to the roadside charging station paradigm may mean that the approach to refueling vehicles will itself need to undergo a larger paradigm shift. This could involve novel solutions such as swappable battery packs, or Vehicle-to-Grid (V2G), wherein electric vehicles are treated as energy storage for the grid and kept charged during off-peak hours, but then being able to reverse-charge during peak electricity usage periods to provide energy to the electrical grid if needed (Marcotte, 2021). Alternatively, from a non-infrastructure standpoint, further advancements in battery technology, such as solid-state batteries with higher energy densities and faster charging could help mitigate these issues.

Finally, outside of paradigm shifts in the underlying technology of EVs and supporting energy infrastructure, the automotive industry itself is undergoing a paradigm shift in how engineering is performed and businesses are run. The Chevy Bolt fires serve as a case study in this industry paradigm shift and are arguably a byproduct of this paradigm shift. Any major paradigm shift across an entire industry comes with inherent risks, due to the sheer scale at which it happens. At approximately 17 million vehicles purchased in the US each year and projections showing a quarter of new sales being electric by 2035 (Plumer et al., 2021), the scale at which the technology is being adopted makes issues almost inevitable.

Being one of the largest and most established automakers in the world, GM is typically considered a “legacy” manufacturer. According to Wayland and Kolodny (2021), two of the largest problem areas that traditional “legacy” manufacturers face are in software and batteries, two areas where they typically lack expertise, compared to younger rivals, such as Tesla. The organizational and cultural inertia inside an older, established company can make it difficult to change the way products are developed, especially when confronted with a new technological paradigm of electric vehicles that diverges from the practices refined from a century’s worth of developing and manufacturing internal combustion engine vehicles. In the past, the core competency for an automaker was to be able to design and manufacture engines and transmissions, while outsourcing the manufacturing and design of many other parts to suppliers. By contrast, EVs require a much more vertically-integrated approach to manufacturing (Hawkins, 2021). It therefore becomes difficult for an established automaker to continue to produce ICE vehicles to satisfy current demand, while also building new supply chains and restructuring engineering and manufacturing in a short timeframe to satisfy the future demand for electric vehicles.

The supply chain for electric vehicles also faces constraints in both cost and options. According to data collected by Statista (2022), the top four manufacturers of lithium-ion batteries (CATL, LG Chem, Panasonic, and BYD) alone make up over 75% of all lithium-ion battery production worldwide. This consolidated market means that the electric vehicle supply chain is vulnerable; issues in manufacturing at a single battery company can have widespread impacts. In the case of the major recalls involving the Chevy Bolt and Hyundai Kona EV in which batteries posed a risk of spontaneously catching on fire, the issues stemmed from the coinciding of two manufacturing defects with the LG Chem-sourced battery cells. A battery pack typically consists of a large array of hundreds to thousands of individual battery cells. In an individual battery cell, the anode tab connects the negative terminal of the battery to the other battery cells in the module, while the cathode tab serves the same purpose for the positive terminal. A separator is also typically present, separating the anode and cathode of the battery cell. The specific defects in these LG Chem-sourced cells were that the anode tab on an individual cell could be torn and the separator could be folded (Voelcker, 2021). While it was rare that both defects could be present in the same cell, the number of cells in each battery pack compounded by the scale at which these battery packs were produced meant that there were inevitably some packs that had both. In the rare instance that both defects were present in the same cell, a fire could result when the battery was charged too fully. Since these cells were sourced by both Hyundai and GM for their cars, these relatively rare defects on their own ballooned into recalls that affected hundreds of thousands of cars, showing the problem with such a consolidated supply chain.

While battery-electric vehicles generally have a much lower incidence of catching on fire than comparable gasoline vehicles, when an electric vehicle fire does occur, the relative novelty of the technology contributes to additional media scrutiny and widespread interest (Eisenstein, 2021). In the case of the Bolt fires, the negative media attention that the fires themselves attracted was exacerbated by the way that GM handled the recall. GM had to issue three recalls that continued to increase in scope over nearly an entire year, starting in November 13th, 2020 and the most recent on August 20th, 2021, that expanded the recall to include all Bolts that had not yet been considered affected (Voelcker, 2021). This eventually included all Bolts ever produced and led to a temporary suspension of Bolt manufacturing and sales (Shepardson, 2022).

Adding to the situation, according to Lehto (2021), was the confusing and unclear messaging to owners about what to do. In the initial November 2020 recall, GM instructed owners to avoid charging their Bolts over 90 percent while engineers investigated the root cause (Lambert, 2020). After nearly two months without any updates to owners, a software fix was finally rolled out on April 21st, 2021, which turned out not to solve the underlying issue--additional vehicles with the software fix were reported to have still caught on fire (Graham, 2021). Additional fires in early July then led to the second expanded recall by GM, with the additional guidance to owners to include instructions to avoid running the battery down to below 70 miles of range. Then, out of an "abundance of caution," GM expanded the recall to include all Bolts in August (Blanco, 2021). The official recall notice now instructs owners of these vehicles to avoid charging over 90%, discharging below 70 miles of remaining range, charging indoors unattended, and parking too close to other vehicles or structures, significantly limiting the capability of the vehicle and causing inconvenience for owners (Voelcker, 2021).

The botched handling of the recall and the software fixes that didn't work helps to characterize the "blind spot" that legacy automakers such as GM have with software. With EVs, software has grown increasingly more important. In the past, the existing paradigm was that, once a car was sold to a customer, it was generally "finished." With the advent of over-the-air software updates, the experience of using a car can be transformed years after it has left the factory. Companies newer to the automotive industry have the advantage of being able to already have software as a core competency, by ingraining the culture and practices of traditional Silicon

Valley technology companies, while legacy automakers likely attempt to fit software competency into their existing culture and practices, which can be at odds.

In this research paper, examining the case study of the Chevy Bolt fires has served as a good framework for looking at the underlying challenges faced by the automotive industry in the major paradigm shift away from ICE vehicles to electric vehicles. However, it may not sufficiently cover all of the problem areas. Additionally, of the smaller necessary paradigm shifts discussed, there was not a determination or specific research into which of these paradigm shifts is quantifiably more impactful for the adoption of electric vehicles. Future research should focus on determining the relative importance of each, in order to better inform industry leaders on which areas should receive a stronger focus and more resources.

Conclusion

After over a century of the internal combustion engine as the dominant paradigm, the electric vehicle has begun to gain traction in becoming the new paradigm, but still faces significant challenges. This paradigm shift has been convoluted and characterized by various limitations that require smaller paradigm shifts to occur, notably in battery technology, energy infrastructure, and the way automakers operate, from the approach to engineering and designing vehicles to manufacturing and supply chain processes. The ongoing paradigm shift in the automotive industry from the ICE vehicle to the electric vehicle will be one of the most consequential technological paradigm shifts of the 21st century, once these smaller paradigm shifts complete. Addressing the individual challenges associated with these smaller paradigm shifts will help to ease the accelerating transition in the coming years and make electric vehicle technology more accessible and allow it to become established as the new paradigm.

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